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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 603

A PRELIMINARY STUDY OF FLAME PROPAGATION
IN A SPARK-IGNITION ENGINE

By A. M. Rothrock and R. C. Spencer
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SUMMARY

The N.A.C.A. combustion apparatus was altered to operate as a fuel-injection, spark-ignition engine, and a preliminary study was made of the combustion of gasoline-air mixtures at various air-fuel ratios. Air-fuel ratios ranging from 10 to 21.6 were investigated. Records from an optical indicator and films from a high-speed motion-picture camera were the chief sources of data. Schlieren photography was used for an additional study.

The results show that the altered combustion apparatus has characteristics similar to those of a conventional spark-ignition engine and should be useful in studying phenomena in spark-ignition engines. The photographs show the flame front to be irregularly shaped rather than uniformly curved. With a theoretically correct mixture the reaction, as indicated by the photographs, is not completed in the flame front but continues for some time after the combustion front has traversed the mixture.

INTRODUCTION

During the last several years the study of flame propagation in internal-combustion engines has been greatly benefited by the use of photography as a research instrument. The first photographic results were obtained with small glass windows placed in the combustion chamber. These results were followed by others obtained with a narrow glass window across the whole of the chamber. In 1934 the N.A.C.A. presented results obtained with an apparatus whereby high-speed motion pictures could be taken of the fuel injection and the flame propagation over a large portion of the combustion chamber. This apparatus was used to investigate the fuel injection and combustion in a

compression-ignition engine. In 1935 Holfelder (reference 1) presented results obtained with another type of apparatus for taking high-speed motion pictures of fuel injection and combustion with auto-ignition. The first published results of high-speed motion pictures of flame propagation in a spark-ignition engine were presented by Withrow and Rassweiler (references 2 and 3) in 1936.

During 1936 the N.A.C.A. combustion apparatus was equipped with a cylinder head suitable for taking high-speed motion pictures of combustion in a spark-ignition engine. A glass window sufficiently large to photograph half the combustion space was installed in the cylinder head. With this apparatus in conjunction with a high-speed motion-picture camera, a preliminary study was made with the apparatus operating as a fuel-injection, spark-ignition engine. In addition to the high-speed motion pictures of the flame propagation, schlieren photographs were taken of the combustion. In this latter case the changes in the index of refraction of the combustion gases are recorded. It is the purpose of this report to present the results obtained in the preliminary tests.

APPARATUS AND METHODS

The N.A.C.A. combustion apparatus has been described in detail in reference 4. Essentially it is a 5- by 7- inch single-cylinder test engine with a glass window installed in the cylinder head so that the injection and combustion of the fuel can be photographically recorded. The engine is driven at the desired speed by an electric motor and is then fired for only one cycle, by injecting and igniting a single charge of fuel. A constant engine-jacket temperature is maintained by circulating glycerin through the jacket.

A diagrammatic sketch of the apparatus is shown in figure 1. The cylinder head is of the pent-roof type and the combustion chamber is similar in shape to the one used by Schey and Young in their tests on fuel injection with spark ignition (reference 5). In the altered arrangement the space normally occupied by the two exhaust valves on one side of the head is used for the glass window. Inasmuch as the engine fires only once, the two remaining valves operate simultaneously and serve both for intake and exhaust. The valves were timed to open 55° before

bottom center on the power stroke, remain open during exhaust and intake, and close 35° after bottom center on the following compression stroke.

Six spark-plug openings are provided in the cylinder head, thus affording alternate positions for the injection valve, spark plugs, and auxiliary fittings.

Preliminary tests with the apparatus showed that the conventional battery-ignition system was too erratic in timing to be of use in closely controlled tests. The variation was often as great as $\pm 10^{\circ}$. A spark system was installed employing a condenser discharge through an induction coil with the discharge occurring on make instead of break as in the conventional system. Maximum variation in timing with this system was about $\pm 1^{\circ}$ of crankshaft rotation.

The observation window consists of two heavy glass plates mounted one behind the other with an air space between. Compressed air is admitted to the space between the plates. The plates are 1 inch thick, $3\text{-}3/8$ inches wide, and 6 inches long. They are mounted with copper-asbestos gaskets and give a clear opening $2\text{-}1/2$ by 5 inches.

The injection system, a cross section of which is included in figure 1, is spring operated. The spring is held compressed by a rocker arm, thus holding the lapped plunger retracted and leaving a port uncovered in the side of the sleeve. Fuel is circulated under pressure by a primary pump through the sleeve and thence to the injection valve, through the hollow stem in this valve and back to the fuel tank (reference 4). For the injection of the fuel, the rocker arm is released by a drop cam and the plunger is driven forward by the spring. The port is covered by the plunger at the start of travel and the fuel is delivered to the injection valve at a pressure of about 2,500 pounds per square inch. The fuel quantity is regulated by changing the length of the plunger travel. This system gives consistent fuel weights, and small changes in injection-valve opening pressure have relatively slight effect on the amount of fuel injected.

The injection nozzle, a sketch of which is shown in figure 2, is similar to the one used by Schey and Young in the work reported in reference 5.

The injection valve was mounted opposite the intake valves so that the fuel was injected counter to the intake air flow. Injection was timed to start 20° after top center on the intake stroke and the injection period for the largest fuel quantities was about 120° .

The pressure indicator is of the optical type, consisting of a pivoted mirror actuated by a diaphragm and reflecting a light beam to a rotating film drum. (See reference 6.) A steel blank, which fits into the window opening, is used for mounting the indicator directly in the combustion-chamber wall. When flame photographs were taken, the indicator was mounted by an adapter in a spark-plug opening. Records taken with the indicator in the spark-plug position are affected by severe vibrations of the air column in the adapter but are useful in indicating the general nature of the explosion.

With the high-speed motion-picture camera described in reference 7, photographs can be taken at rates up to 2,500 frames a second. Most of the photographs shown in this paper were taken at about 2,000 frames a second. The camera was mounted above the combustion apparatus with the camera lens on the center line of the window and parallel to the plane of the window. Thus a considerable portion of the interior of the cylinder was in the field of view; however, only the space in the cylinder head was in focus. The fuel used in most of the tests was gasoline to Army specification Y-3557-6, having an octane number of 87. For the leaner mixtures the flame did not record well on the film; therefore, sodium hydroxide was added to the fuel in the proportion of 10 cubic centimeters of a 4-percent solution in alcohol to 1 gallon of fuel. The actinic value of the flame was thereby increased sufficiently to record and no apparent effect could be noted on the combustion as shown by indicator cards; also, the rates of flame propagation, determined for the mixtures which could be photographed without use of sodium hydroxide, were not affected when sodium hydroxide was added.

It was considered advantageous, when the combustion was being photographed, also to photograph the fuel spray as it occurred on the intake stroke. The fuel spray was illuminated by mounting a small hemispherical lens in the spark-plug opening opposite the injection valve and focusing the light from a high-intensity arc on this lens.

Throughout the tests the following conditions were

maintained constant except where otherwise noted:

Engine speed 1,500 r.p.m.

Engine-jacket temperature . . . 250° F.

Spark advance 20°

Two spark plugs were located on opposite sides of the combustion chamber and at right angles to the injection valve.

The schlieren photographs were taken by using a high-intensity arc light as a source. A diagrammatic sketch of the optical set-up is shown in figure 3 and a description of the schlieren method is given in reference 8. A mirror was mounted on the piston because it was necessary to have the light pass through the medium being photographed. The condensing lens in front of the arc brought the light to a focus on a hole in a metal disk placed at the focus of the second lens. The diverging rays entering the second lens left this lens as parallel rays. By means of the mirrors shown, the rays passed through the gases in the combustion chamber and returned through the second lens. By a suitable adjustment of the mirrors, the image of the spot source was thrown somewhat out of line with the source. It was therefore possible to use a small mirror which reflected the rays so that the image was in a plane at a right angle to the plane of the spot source. The round stop to obtain the schlieren effect was placed in the plane of the image, allowing only an annular ring of light to pass. A plate with a hole for the main image was provided to block off the series of images from the surfaces of the windows. The stop was thus actually a plate with an annular opening. The light transmitted through this ring was directed onto a film mounted on a drum, and the image of the combustion chamber, formed by the second lens, came to a focus on the front of the drum. A mask having a 1/8-inch slit was placed in front of the drum, so that only a strip across the chamber was photographed. The part of the image transmitted by the slit corresponded to a 1/4-inch strip, parallel to and about 3/4 inch from the center line joining the two spark plugs at 90° to the injection-valve position shown in figure 1. A continuous, or streak, record was taken with this set-up instead of the high-speed motion pictures.

With this set-up the light from the burning fuel was

insufficient to record on the film. The record obtained was that from the arc-light source; therefore, the photographic results showed only the changes in the index of refraction of the gases in the combustion chamber. The combustion front is accompanied by a marked temperature increase and was therefore recorded on the film. Other phenomena, which are not shown in photographing the flame front, are shown by the schlieren method.

REPRODUCIBILITY OF RESULTS

Fuel weights per injection were checked by weighing single injections. The variation in weight was about $\pm 2\frac{1}{2}$ percent. Tests made by injecting several fuel charges into a bottle indicated that the loss in recorded weight caused by evaporation was not great enough to be important.

Variation in spark timing at first caused considerable differences between individual explosions but they were minimized by the installation of the condenser-discharge spark system. Even with the same spark timing and fuel weight per injection, indicator cards of successive explosions still showed considerable variation, both in maximum pressure and in rate of pressure rise. Hence it was necessary, when tests were being made, to take about 10 indicator cards at each condition. From these 10 cards, one card was selected as representative of the average explosion. The glass plates were then installed, the indicator was placed in one of the spark-plug openings, and three high-speed motion pictures of the flame formation were taken. The composite of eight indicator cards in figure 4 shows the extent of variation between successive explosions at the same conditions. Examination of various indicator cards from spark-ignition engines, made with a Farnboro indicator, indicates that the variation between successive explosions in an engine is not materially different from that between successive explosions in the combustion apparatus.

RESULTS AND DISCUSSION

Representative indicator cards for each air-fuel ratio were selected and replotted as pressure-volume diagrams. From these diagrams the respective indicated mean effective

pressures were determined (fig. 5). The fuel consumption was computed from the indicated mean effective pressure and the recorded fuel charge. No correction was made for the hysteresis of the indicator diaphragm because the data are used only for comparative purposes; the recorded i.m.e.p. is therefore too high. It is seen from the figure that the air-fuel ratio for maximum power was in the neighborhood of 12, and for "best economy" was about 16. Available data for laboratory dynamometer tests of a modern aircraft engine give values of from 12.5 to 13 for maximum power and from 16 to 16.5 for best economy.

High-speed motion pictures showing the effect of air-fuel ratio on the flame formation are reproduced in figures 6 and 7. The bright spots visible in the center of the frames before combustion begins are caused by the reflection of light from the piston crown as it rises on the compression stroke. At air-fuel ratios differing greatly from the theoretically correct one, the rate of flame propagation was somewhat slower than at the optimum ratio. The irregular flame fronts are characteristic of virtually all the photographs that have been taken. It frequently happens that when the two flame fronts approach each other, a projection on one flame front matches a corresponding indentation on the other front. (See fig. 7, air-fuel ratio of 10.) The various irregularities are never the same for any two photographs with the exception that the last part of the charge to burn is usually in the same part of the chamber.

Another feature characteristic of many of the photographs is the appearance of small spots of brighter luminosity throughout the flame. These spots are believed not to be caused by uneven distribution of the fuel inasmuch as 100-octane gasoline, no more volatile but differing in chemical characteristics from the fuel used in most of these tests, burned with very uniform illumination throughout the chamber; also, the bright spots appear in very lean mixtures and it would scarcely seem probable that, since the fuel is injected, any spots of extreme richness would exist in such a mixture.

In the frames marked A for the photographs at air-fuel ratios of 10 and 12.5 (fig. 6), an area of very bright illumination appears on the left side of the window (the point near the peak of the pent-roof cylinder head). In the succeeding frames the bright illumination spreads farther across the window and then gradually disappears.

Rassweiler and Withrow show similar photographs in reference 3 and attribute the effect to burning lubricating oil. The piston of the N.A.C.A. combustion apparatus, however, is lubricated by graphite, and the engine is operated without oil in the crankcase; hence another cause must be sought. The effect appears only at the lower air-fuel ratios and so is evidently associated with incomplete combustion.

Visual observations of the flame at various air-fuel ratios also afforded an interesting means of comparison. With no sodium hydroxide in the fuel, the flame appeared distinctly yellow at the lower air-fuel ratios. At ratios near the theoretically correct one for complete combustion, the flame appeared blue shot through with yellow streaks, and at the very high ratios it appeared pale blue.

A striking feature appeared in the photographs for the ratios of 18.5 and 21.6. Here, the flame completely traversed the chamber at a somewhat slower rate than at lower air-fuel ratios. Then, after the charge had apparently been burned, afterburning began and continued after the exhaust valve opened. To the eye this afterburning (in the exhaust) was characterized by an intense violet color. Enlargements of the photograph showing afterburning at a ratio of 18.5 are shown in figure 8, and it is seen that the flame had traversed the chamber by 30° after top center. Inasmuch as the piston had moved only $6/10$ of an inch in this time, there is little doubt but that the flame had completely traversed the charge in the vertical as well as in the horizontal direction. Hence the afterburning is evidently a reillumination of the charge. At an air-fuel ratio of 21.6, the original film shows that the flame had traversed the chamber by 50° after top center. The actinic value of the flame, however, was so weak that the flame did not show in a reproduction. The afterburning at this ratio is decidedly brighter than at a ratio of 18.5.

Marek and Hahn (reference 9), in a discussion of knocking in internal-combustion engines, cite works of other investigators which seem to show that combustion in the flame front is not complete and that the reactions continue for some time after the flame front has passed through the charge.

High-speed motion pictures and schlieren photographs

of knocking and nonknocking explosions are shown in figure 9. The upper strip of each pair of pictures is a high-speed motion picture, and the lower strip is a schlieren photograph. The photographs were not taken simultaneously, and the motion picture of the knocking explosion shows that the flame crossed the chamber sooner than was the case for the schlieren record for the same conditions. It should be kept in mind, when looking at the schlieren photographs, that they are records of a change in index of refraction of the charge. The combustion front is visible because of the temperature change.

The frame marked A, in the motion picture of the knocking explosion, shows a sudden large increase in the area covered by the flame. This increase is probably caused by auto-ignition of the part of the charge farthest from the spark plug. The next frame shows the chamber filled with flame and very brightly illuminated. The sudden extremely brilliant illumination is characteristic of the knocking explosions and the brilliance of the illumination apparently depends upon the violence of the knock. The flame before top center is shot through with small areas of brighter illumination.

The schlieren photograph of a knocking explosion shows that the flame front traveled almost across the chamber when some reaction caused a sudden reverse movement in the gases, followed immediately by detonation, which set up very violent waves in the chamber. The sudden backward movement in the gases is characteristic of the extremely violent knocking explosions.

Examination of the photographs of nonknocking explosions at once discloses some important differences from those under knocking conditions. For the nonknocking explosions, the burning throughout the chamber, as shown by the high-speed motion pictures, is very uniform in its illumination. The discontinuities in the schlieren record of the combustion front are not characteristic and are caused by the irregularities in the front as it advances parallel to the slit and then spreads at right angles to the general direction of travel. The reverse movement of the gases after the flame front has crossed the chamber is characteristic of all the schlieren photographs of nonknocking explosions. The discontinuity in the record, 6° or 7° after top center, was caused by a slight sidewise motion of the piston, which changed the angle of the light beam as reflected from the mirror on the piston.

In both of the schlieren records, compression waves can be distinguished ahead of the flame front, but no evidence has been seen of any wave traveling at any decidedly higher speed than the flame front, such as has been photographed by Payman and Titman in explosions of gaseous mixtures in tubes (reference 10).

Figure 10 shows two schlieren photographs taken when the engine was operating on two spark plugs. These photographs show the combustion fronts starting at the two plugs, apparently passing directly through each other without interference, and continuing across the chamber. After traversing about half the remaining distance, the two fronts became indistinct and merged with the general pattern of the burning. Thus it is evident that some reaction, which changed the density of the charge, continued after the combustion front had passed through. The depth of the reaction zone, as measured from the negative, varied between 1 and 1-1/2 inches.

CONCLUSIONS

1. Data obtained with the N.A.C.A. combustion apparatus operating as a spark-ignition engine can be compared with similar data from spark-ignition engines, and photographs of the combustion in the apparatus should be useful in interpreting phenomena in spark-ignition engines.
2. The flame front as it moves outward from the point of ignition is irregularly shaped rather than smoothly curved, and does not assume the same form for successive explosions.
3. The combustion process is not completed in the flame front but continues for some time after the flame front has passed through the charge.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 20, 1937.

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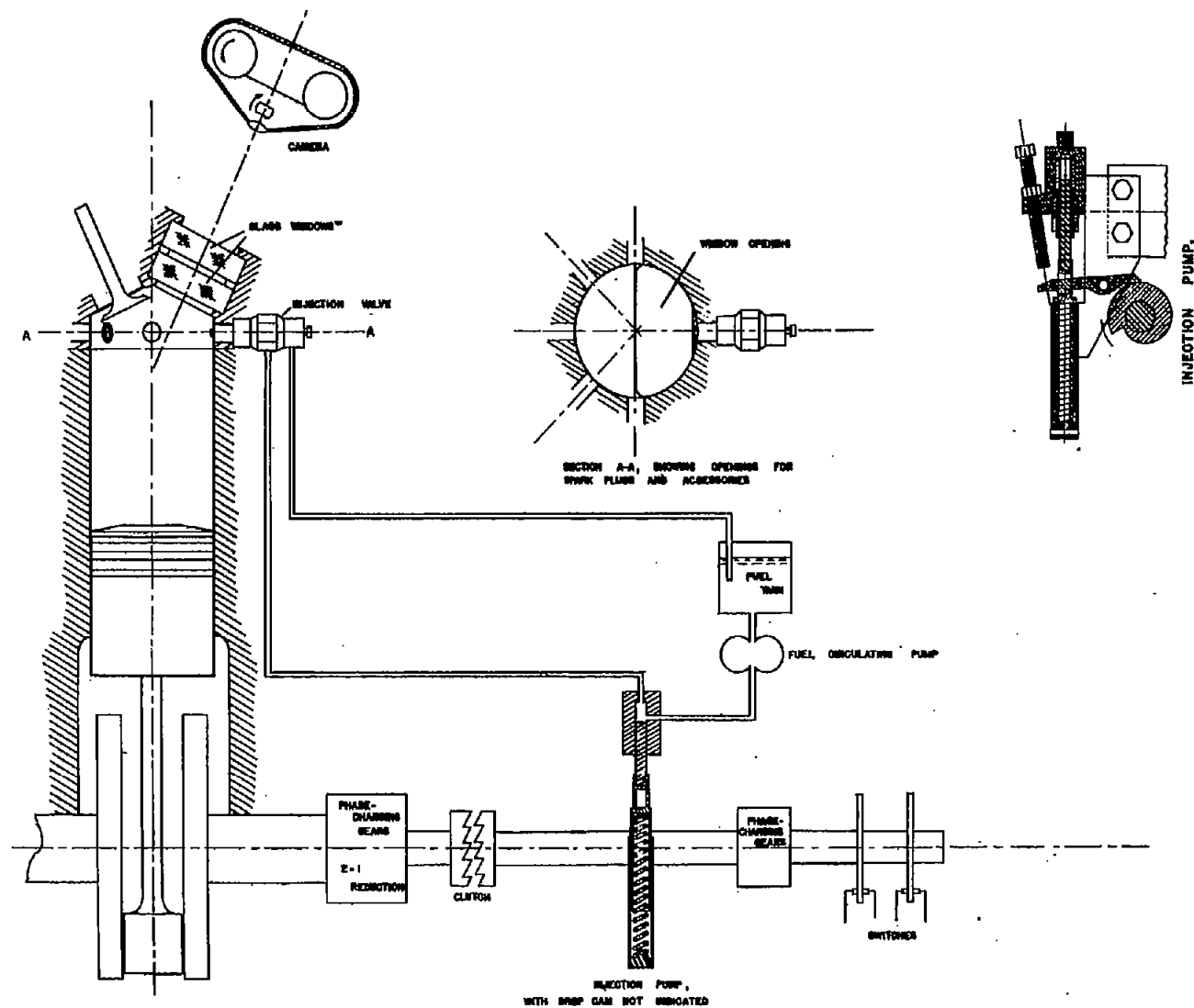


Figure 1.—Diagrammatic sketch of combustion apparatus.

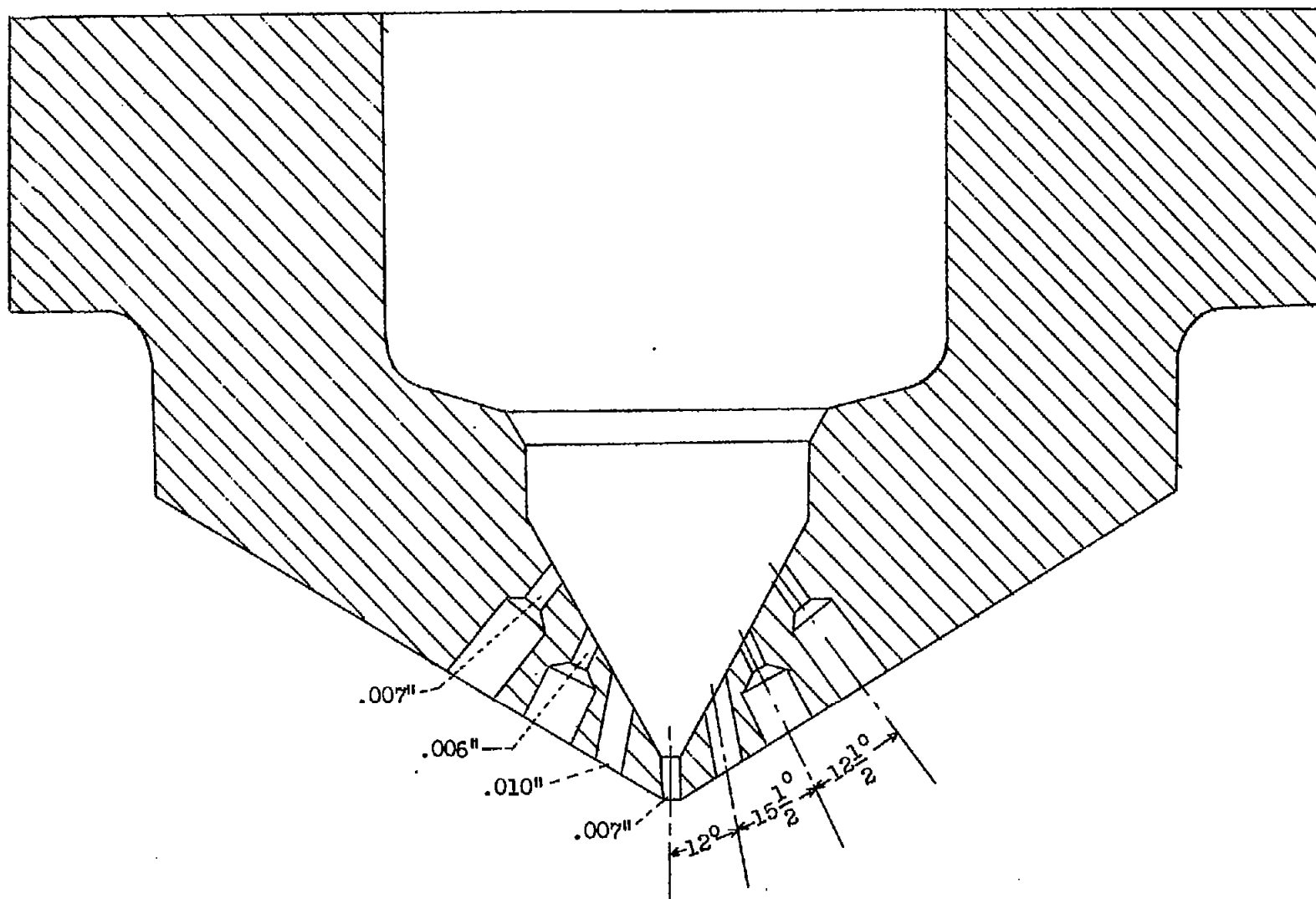
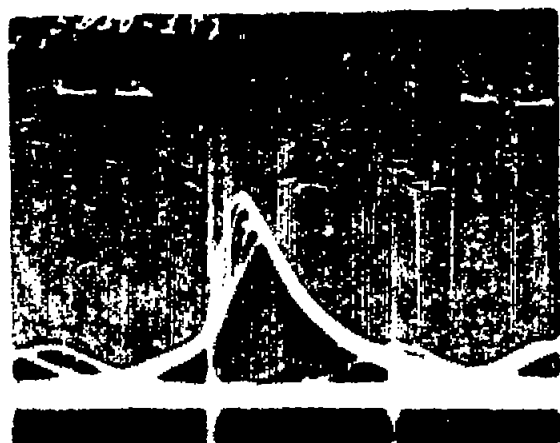


Figure 2.- The 7-orifice nozzle.



Engine speed,
1500 r.p.m.
Compression
ratio, 7.0.
Two spark plugs.
Air-fuel ratio, 10.
Injection start
20° A.T.O. on
intake stroke.
Engine-jacket
temperature,
250° F.
Spark advance, 20°

Figure 4. - Composite of eight indicator cards
taken under the same conditions.

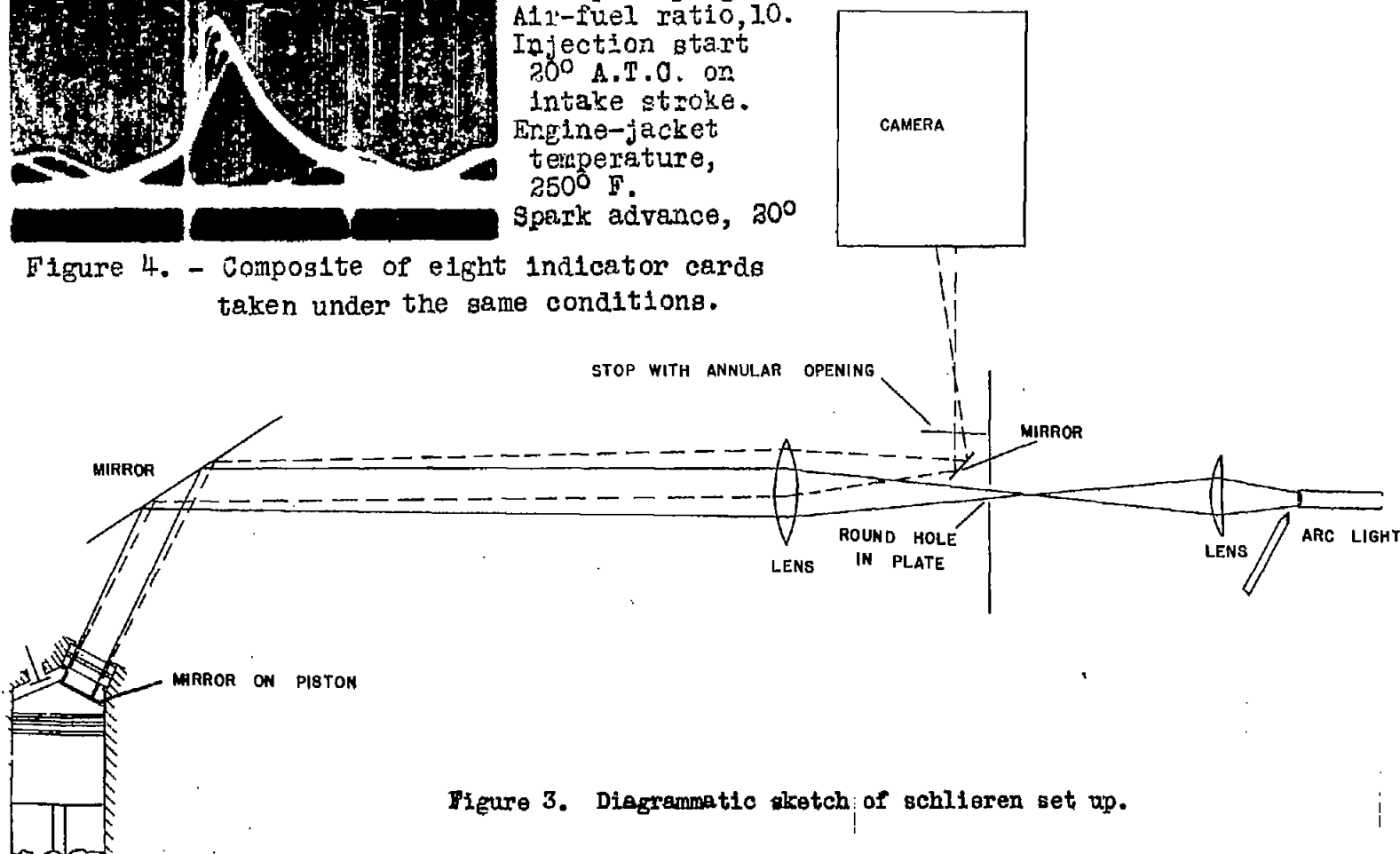


Figure 3. Diagrammatic sketch of schlieren set up.

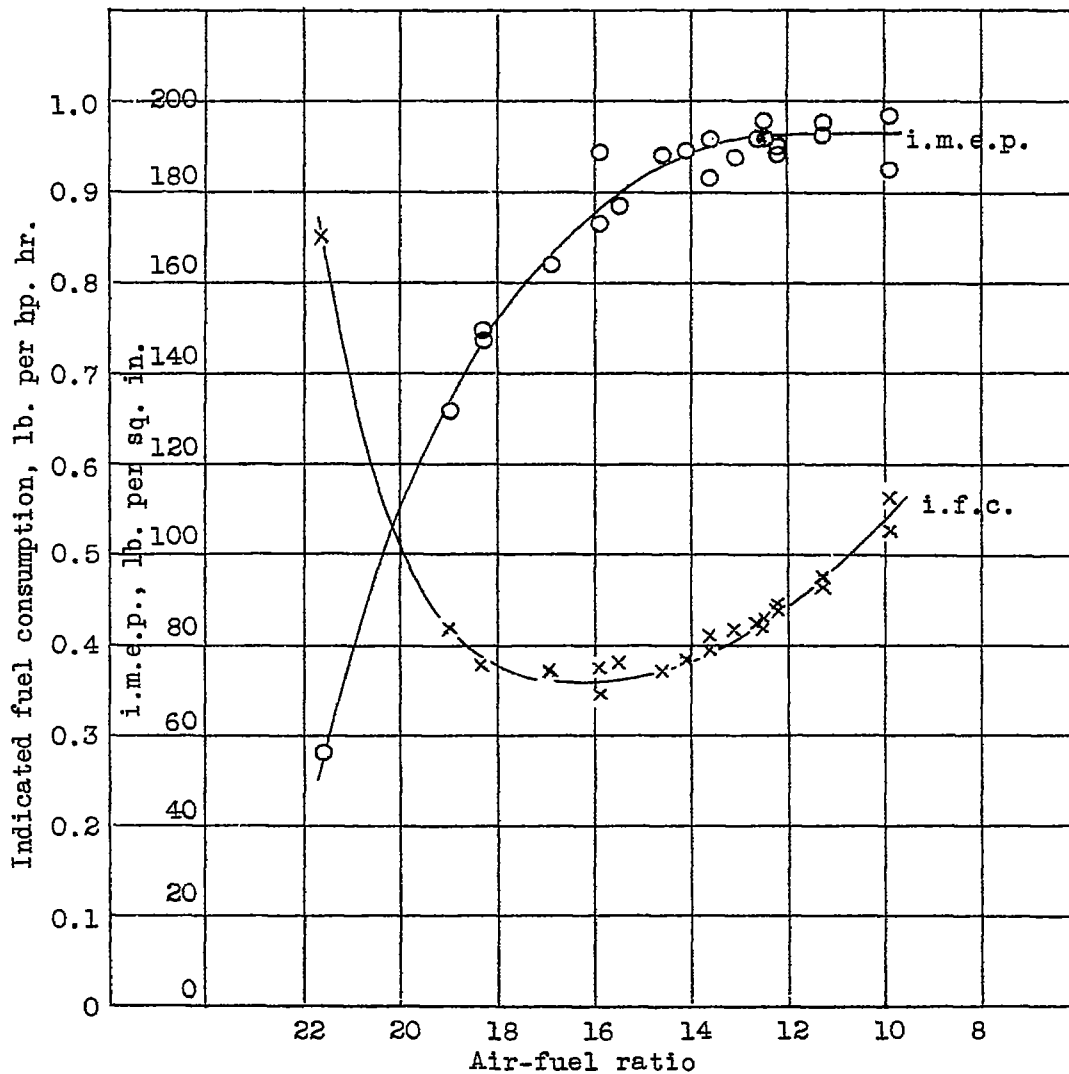


Figure 5.- Effect of air-fuel ratio on indicated mean effective pressure and indicated fuel consumption.

| | |
|----------------------------|--|
| Engine speed, 1,500 r.p.m. | Engine jacket temperature 250°F. |
| Compression ratio, 7 | Spark advance 20° |
| Two spark plugs | Injection start 20° A.T.C. on intake stroke. |

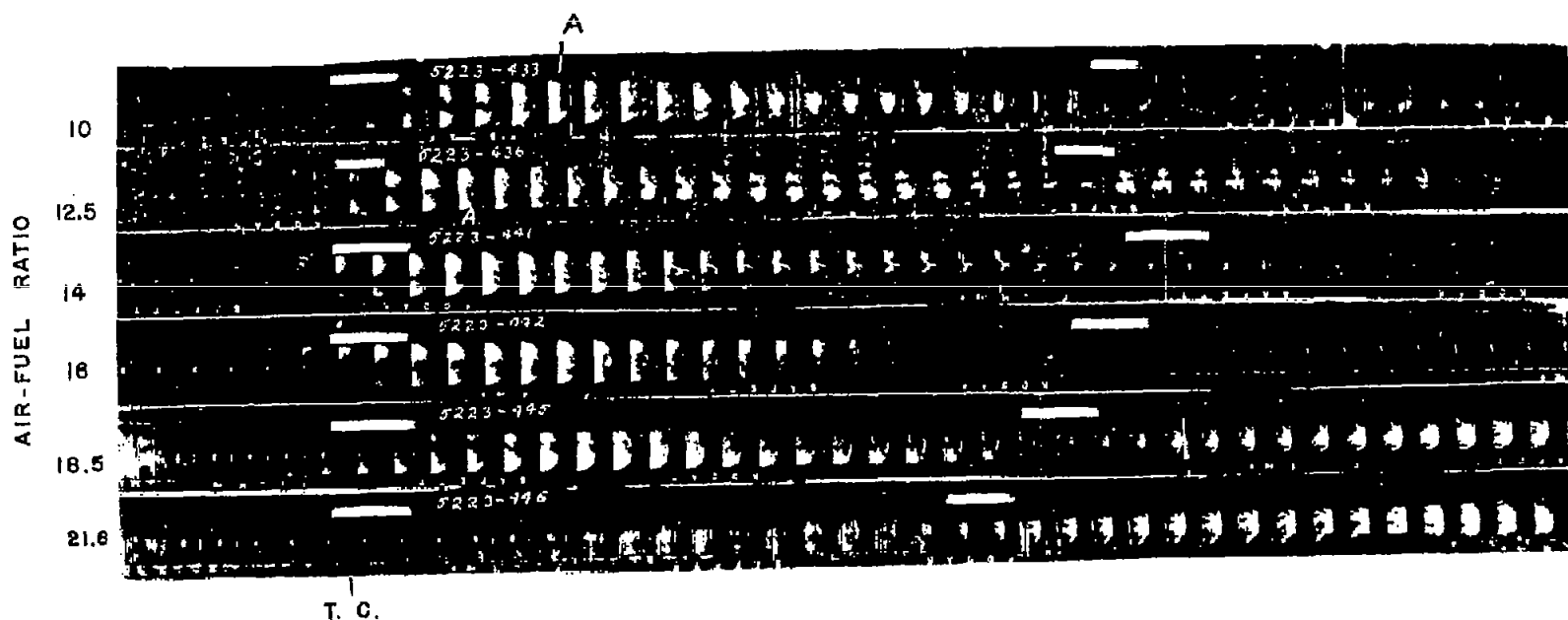


FIGURE 6 EFFECT OF AIR-FUEL RATIO ON FLAME PROPAGATION.

WHITE MARKS ON UPPER EDGE OF EACH FILM CORRESPOND
 TO TOP CENTER AND 90° AFTER TOP CENTER.
 ENGINE SPEED, 1500 R.P.M. ENGINE JACKET TEMPERATURE, 250 °F
 COMPRESSION RATIO, 7.0 SPARK ADVANCE 20°
 TWO SPARK PLUGS
 INJECTION START, 20° A.T.C. ON INTAKE STROKE

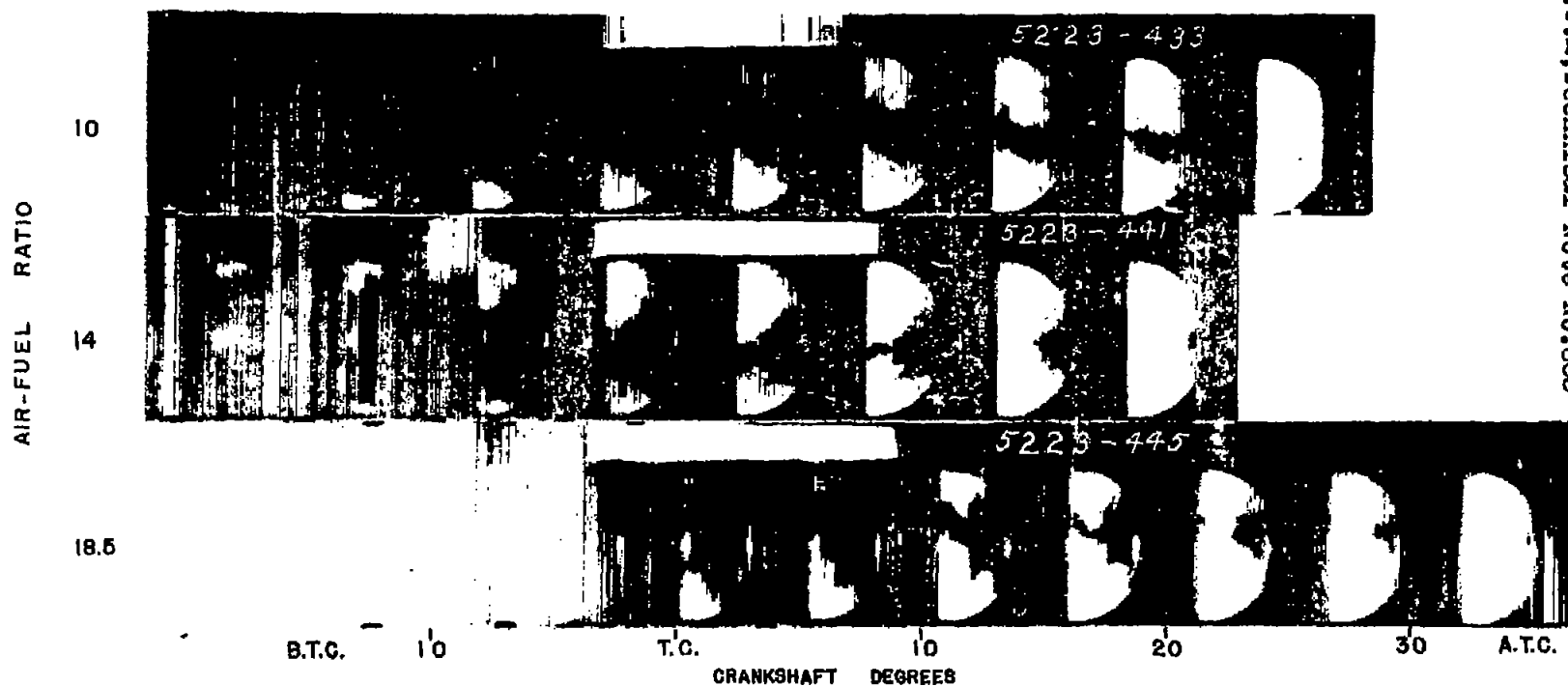


FIGURE 7.- ENLARGEMENTS OF PHOTOGRAPHS OF FLAME FORMATION AT

AIR-FUEL RATIOS OF 10, 14, AND 18.5

ENGINE SPEED, 1500 R.P.M.

ENGINE JACKET TEMPERATURE, 250 °F.

COMPRESSION RATIO, 7

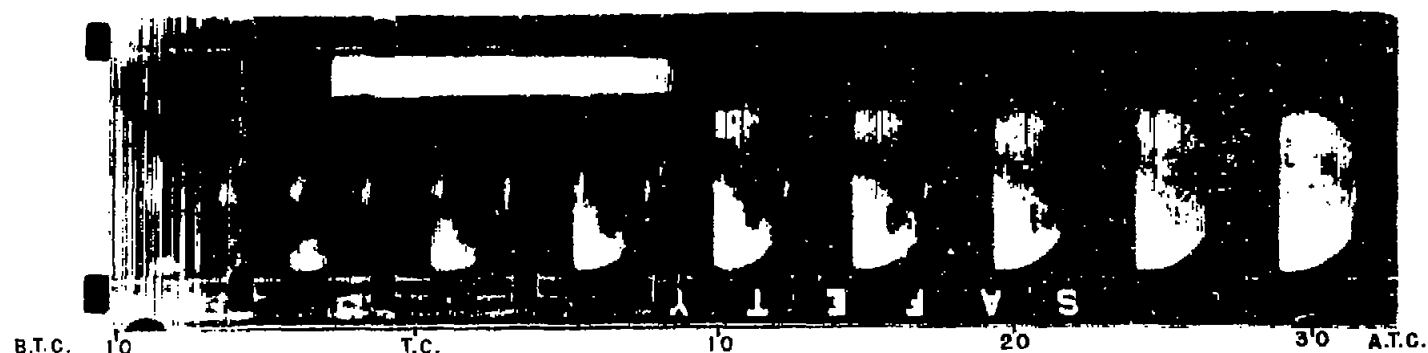
SPARK ADVANCE, 20°

TWO SPARK PLUGS

INJECTION START, 20°

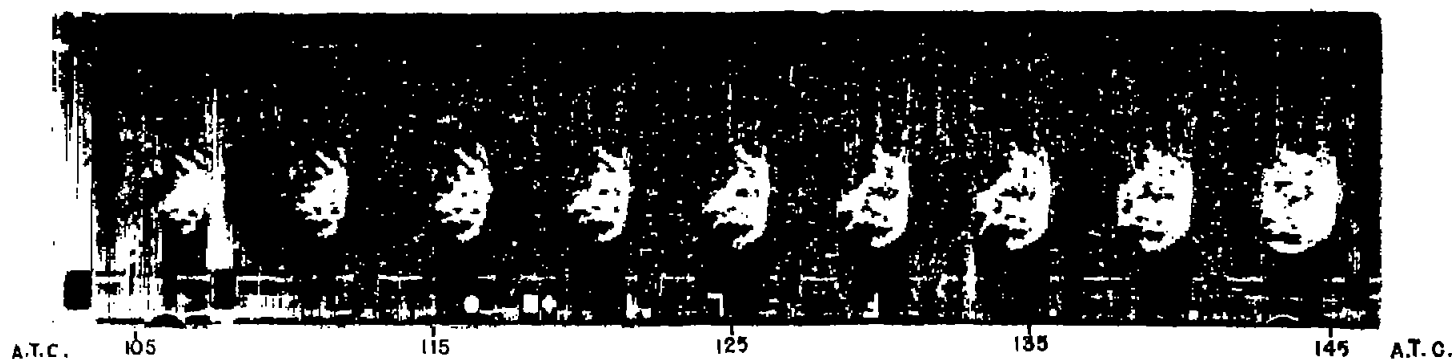
A.T.C. ON INTAKE STROKE

NACA
12113



CRANKSHAFT DEGREES

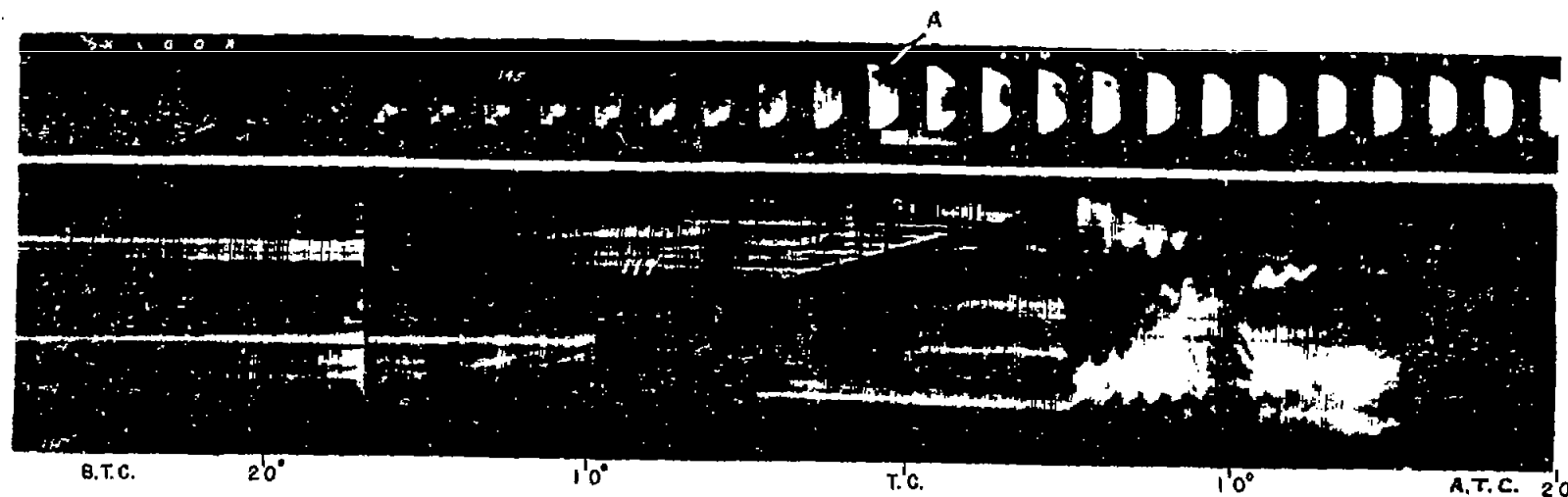
INITIAL BURNING



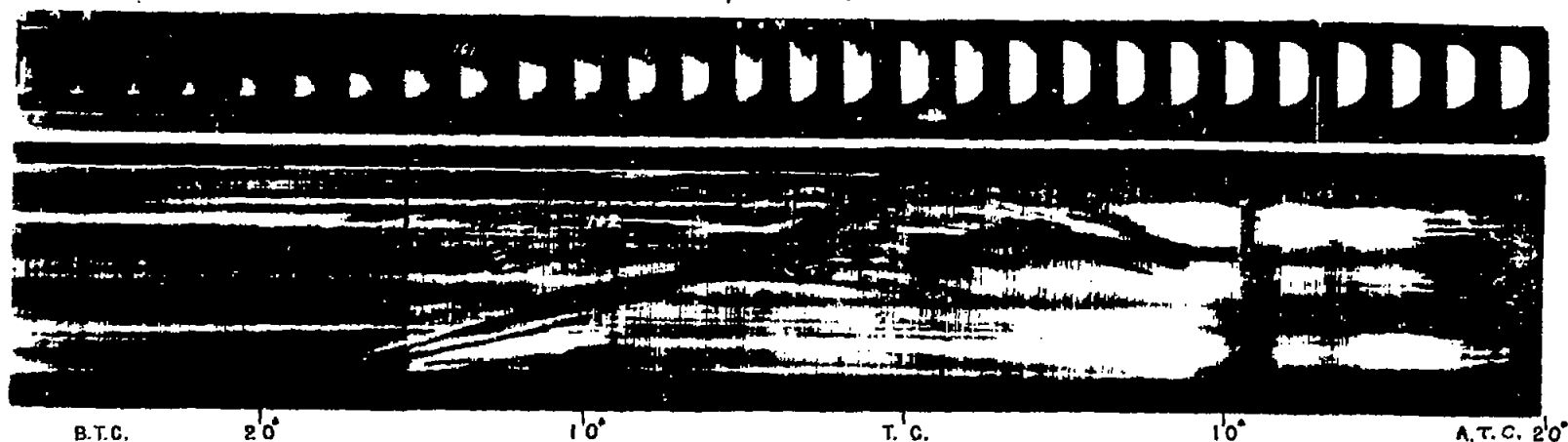
CRANKSHAFT DEGREES

AFTERBURNING

FIGURE 8. AFTERBURNING OF LEAN MIXTURE, AFTER FLAME
HAS TRAVERSED CHARGE AIR-FUEL RATIO, 18.5 EXHAUST VALVES OPEN 125° A.T.C.
ENGINE SPEED, 1500 R.P.M. ENGINE JACKET TEMPERATURE, 250 °F TWO SPARK PLUGS
COMPRESSION RATIO, 7.0 SPARK ADVANCE 20° INJECTION START 20° A.T.C. ON INTAKE STROKE



18-OCTANE FUEL, KNOCKING



100-OCTANE FUEL, NONKNOCKING

Figure 9.-

HIGH-SPEED MOTION PICTURES AND SCHLIEREN PHOTOGRAPHS OF EXPLOSIONS IN A GASOLINE ENGINE, ONE SPARK PLUG

ENGINE SPEED, 500 R.P.M.

ENGINE JACKET TEMPERATURE, 250 °F

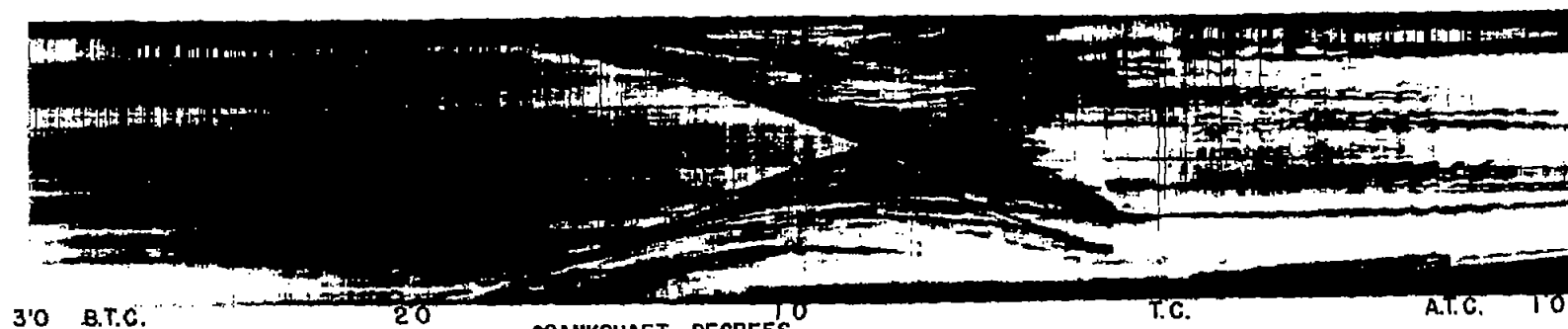
COMPRESSION RATIO, 7.0

SPARK ADVANCE, 30°

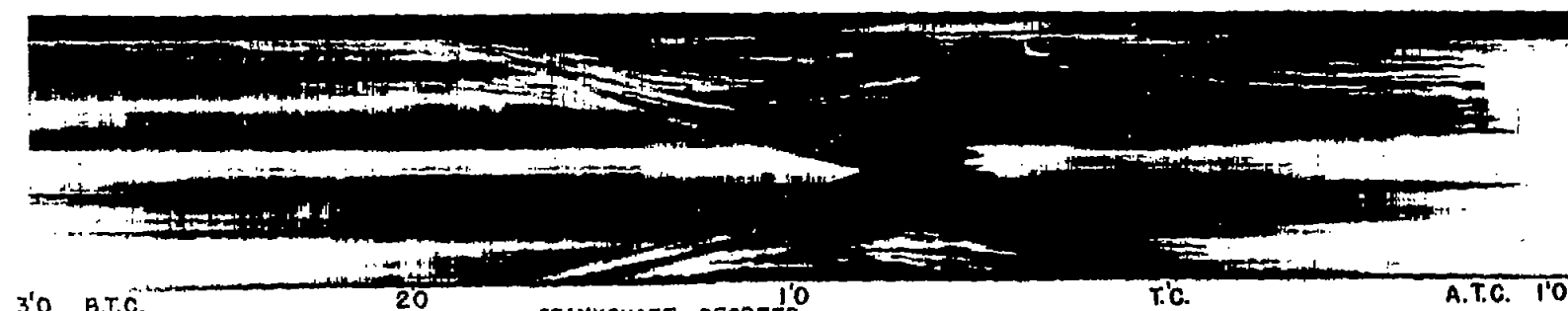
INJECTION START, 20° A.T.C. ON INTAKE STROKE

AIR-FUEL RATIO, 14

Fig. 9



CRANKSHAFT DEGREES
KNOCKING EXPLOSION, *COMMERCIAL AUTOMOBILE GASOLINE.*



CRANKSHAFT DEGREES
NON-KNOCKING EXPLOSION, *AUTOMOBILE GASOLINE PLUS ETHYL FLUID.*

FIGURE 10. SCHLIEREN PHOTOGRAPHS SHOWING TWO FLAME FRONTS PASSING THROUGH EACH OTHER
ENGINE SPEED, 500 R.P.M. ENGINE JACKET TEMPERATURE, 250°F
COMPRESSION RATIO, 7.0 SPARK ADVANCE, 30°
TWO SPARK PLUGS
INJECTION START, 20° A.T.C. ON INTAKE STROKE